STUDIES FOR STUDENTS

CONTRIBUTIONS TO THE STUDY OF RIPPLE MARKS

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The two interesting papers on ripple marks by E. M. Kindle and J. A. Udden, published in the *Journal of Geology* for October-November, 1914, and February-March, 1916, respectively, suggest that readers of the *Journal* might be interested in a brief review of certain previous contributions to the subject, particularly since most of the questions raised by these two writers have occupied the attention of earlier investigators. In connection with a study of wave action, I have recently had occasion to consult a number of reports on ripple marks, and offer in the following paragraphs a synopsis of some essays not mentioned by Kindle or Udden. No attempt has been made to compile a complete bibliography of the subject, but reference is made to most of the more important papers which have come to the writer's attention.

The accumulation of sand and finer débris in parallel ridges and troughs somewhat resembling water waves in form, though not at all in origin or in method of formation, was long ago recognized as a normal product of wave and current action. Under various names, such as "current mark," "wave mark," "ripple drift," "current drift," and "friction markings," the phenomenon now generally known as ripple mark has repeatedly been described. Although not infrequently found on sandy beaches, ripple marks are perhaps better developed on tidal flats and over the broad bottoms of shallow estuaries, lakes, and ponds. They are not unknown on the deeper sea floor of the off-shore zone, where their occurrence to a depth of over 600 feet has been demonstrated. Ripple marks which are exposed by the falling tide may be

delicately dissected by rill marks, an example of this phenomenon having been described by Dodge.[1]

Among the earlier accounts of ripple marks, one of the most interesting is based on the little-known work of an ingenious French engineer named Siau.[2] In 1841 he published a brief note entitled "De l'action des vagues à de grandes profondeurs," based on observations of ripple marks in deep water, made with the aid of an ordinary sounding apparatus. While examining ripple marks, visible during quiet water, on the bed of a channel off the west coast of the Isle of Bourbon, Siau noted that the heavier particles of the sand tended to accumulate in the troughs between the ridges, while lighter material was concentrated along the ridge crests. Profiting by this discovery, he coated a sounding lead with tallow and lowered it to the sea floor where the depth was too great for direct visual observation. When brought to the surface the tallow sometimes retained, adhering to it, only heavy particles of sand, in which case the surface of the tallow had a convex form, showing that it had been pressed down into the trough between two ripples. In other cases the tallow was coated with lighter particles only, and had a concave form, as a result of having been pressed down upon a ripple crest. At great depths, where the ripples were more closely spaced, two parallel bands of materials differing in specific gravity would be impressed upon the tallow at the same time, the heavier material coating a convex ridge, and the lighter a concave depression in the tallow. By this ingenious device Siau was able to prove the existence of ripple marks at a depth of 617 feet.

The ripples described by Siau were believed by him to be due to the back-and-forth currents which are produced on a sea bottom by oscillatory waves. Such ripple marks are called "oscillation ripples," and are characterized by symmetry of crests, neither slope being steeper than the other, since the ridges are built up by currents which operate from both sides with approximately equal

[1] R. E. Dodge, "Continental Phenomena Illustrated by Ripple Marks," *Science*, XXIII (1894), 38–39.

[2] Siau "De l'action des vagues à de grandes profondeurs," *Comptes rendus de l'academie des sciences*, XII (1841), 774, and *Annales de chimie et de physique*, 3^{e} Sér. (1841), 118.

force. The crests are sharp and narrow as compared with the more broadly rounded intervening troughs. De la Beche, in his *Geological Observer* describes another type of ripple mark, produced by the action of a current flowing steadily in one direction over a bed of sand.[1] These "current ripples" have a long, gentle slope toward the direction from which the current comes, and a shorter, steeper slope on the lee side. Sand grains removed from the gentle slope are carried to the crest and dropped down the steeper slope, causing the ripples to migrate slowly with the current, much as sand dunes migrate with the wind.

Sorby gave a very good description of current ripples in *The Geologist* for 1859, but failed to recognize the existence of wave-formed oscillation ripples, although he noted, and even pressed too closely, the analogy between true waves and ripples.[2] For many years current-formed ripples were the only type recognized in most textbooks. In 1882, in opposition to the general view, Hunt claimed that as a rule ripple marks are the product of oscillatory wave action, and supported his claim with observations based on the artificial production of ripple marks, as well as with numerous observations of naturally formed ripples.[3] He was evidently unaware of the fact that Siau had supported the same theory some forty years earlier, and in a later paper he erroneously credited Forel with priority in the recognition of oscillation ripples.[4] Hunt incidentally describes oscillation ripples in his paper "On the Action of Waves on Sea-Beaches and Sea-Bottoms."[5] He also discusses the nomenclature of ripple marks at much length in a paper published in 1904,[6] and elsewhere quotes Lieutenant Damant, R.N.,

[1] H. T. De la Beche, *The Geological Observer* (Philadelphia, 1851), p. 506.

[2] H. C. Sorby, "On the Structures Produced by the Currents Present during the Deposition of Stratified Rocks," *Geologist*, April, 1859, p. 141.

[3] A. R. Hunt, "On the Formation of Ripple-Mark," *Proc. Roy. Soc. London*, XXXIV (1882), 2, 18.

[4] A. R. Hunt, "The Descriptive Nomenclature of Ripple-Mark," *Geol. Mag.*, N.S., I (1904), 411.

[5] A. R. Hunt, "On the Action of Waves on Sea-Beaches and Sea-Bottoms," *Proc. Roy. Dublin Soc.*, N.S., IV (1884), 261–62.

[6] A. R. Hunt, "The Descriptive Nomenclature of Ripple-Mark," *Geol. Mag.* N.S., I (1904), 410–18.

as having observed ripple marks while diving at depths of 60 and 70 feet.[1]

In 1883, the year following the publication of Hunt's earliest paper cited above, there appeared three important essays on ripple marks: one by De Candolle on "Rides formées á la surface du sable déposé au fond de l'eau et autres phénomènes analogues"; another by Forel on "Les rides de fond étudiées dans le lac Léman"; and a third by Darwin "On the Formation of Ripple-Mark in Sand." De Candolle produced ripple marks artificially by experimenting, not only with sand and various substances in powdered form covered by water, but also with liquids of varying viscosity, covered with water and other liquids.[2] Regarding sand or powder mixed with water as a viscous substance, he concluded from his experiments that "when viscous material in contact with a fluid less viscous than itself is subjected to oscillatory or intermittent friction, resulting either from a movement of the covering fluid or from a movement of the viscous mass itself with respect to the covering fluid, (1) the surface of the viscous substance is ridged perpendicularly to the direction of friction, and (2) the interval between the ridges is directly proportional to the amplitude of the friction-producing movement." That ripple marks depend on simple friction alone, and not on any change of level in the covering liquid, such as occurs during wave action, De Candolle proved by an experiment with a rotating disk submerged in a tank of water. After submerging the disk and mixing an insoluble powder in the water, the apparatus was left until the powder settled on the disk and floor of the tank as an even film, and the water came to rest. An oscillatory rotary movement then applied to the disk caused radiating ripples to form upon it, while no ripples formed on the stationary bottom, and the surface of the water remained quiescent. The author concludes that the formation of ripples in sand, whether under currents of air or under water currents, is identical in origin with the formation of water ripples under moving air. If the cur-

[1] A. R. Hunt, "Facts Observed by Lieut. Damant, R.N., at the Sea-Bottom," *Geol. Mag.*, N.S., V (1908), 31–33.

[2] C. de Candolle, "Rides formées à la surface du sable déposé au fond de l'eau et autres phénomènes analogues," *Archives des sciences physiques et naturelles*, 3e Sér., IX (1883), 241–78.

rent moves always in one direction we have intermittent friction due to varying velocities. Otherwise we have oscillatory friction due to alternating change of direction. Current ripples result from the first type of friction, oscillation ripples from the second.

Forel in his excellent essay on "Les rides de fond étudiées dans le lac Léman"[1] sets forth the mature results of studies which had been briefly mentioned by him in three communications of earlier date.[2] Abandoning his first theory, that the formation of ripple marks is dependent in part upon the vertical pressure of water waves upon the bottom,[3] Forel reached the following important conclusions as the result of many careful observations and experiments: (1) Current ripples are asymmetrical and migrate with the current like ordinary sand dunes, whereas oscillation ripples are stationary and symmetrical. (2) Each oscillation ripple is really a composite of two current ripples, resulting from the action of two currents moving alternately in opposite directions, each current attempting to form the ridge into a current ripple migrating with it, but being defeated when the return current tries with equal force to shape the ridge into a current ripple directed in the opposite sense. (3) The length of the water body has no direct effect on the spacing of the ripples. (4) Other things being equal, the ripples are more closely spaced with increasing depth. (5) At a given depth, and with other conditions uniform, the ripples are more widely spaced with increase in coarseness of sand grains. (6) Ripples once formed do not experience a change in spacing as a result of diminishing amplitude of oscillation of the water, although the original spacing does depend upon the amplitude of oscillation, as pointed out by De Candolle. (7) For any given coarseness of sand grains there is a certain mean velocity of the oscillating currents which will produce ripples; lower velocities

[1] F. A. Forel, "Les rides de fond étudiées dans le lac Léman," *Archives des sciences physiques et naturelles*, 3e Sér, X (1883), 39–72.

[2] F. A. Forel, "La formation des rides du Léman," *Bulletin de la Société Vaudoise des sciences naturelles*, X (1870), 518; "Les rides de fond," *ibid.*, XV (1878), P.V. 66–68; "Les rides de fond dans le golfe de Morgues," *ibid.*, 76–77.

[3] F. A. Forel, "La formation des rides du Léman," *Bulletin de la Société Vaudois des sciences naturelles*, X (1870), 518; "Les rides de fond étudiées dans le lac Léman," *Archives des sciences physiques et naturelles*, 3e Sér., X (1883), 40.

will fail to move the sand grains, and hence cannot build ripples, while higher velocities agitate the whole mass of sand so violently that no ripples can form. (8) The formation of ripples is initiated by some obstacle or inequality on the surface of the sand, behind which sand grains accumulate in the eddy caused by its presence; this leaves a furrow on either side of the initial ridge, due to the abstraction of sand accumulated in the ridge; and these furrows in their turn cause additional ridges to develop on their outer margins, and so on. (9) In a given locality, ripple marks almost always form with the same spacing, regardless of the varying intensity of winds and waves affecting the water body; this is in consequence of laws 7 and 6 stated above. (10) The depth at which ripple marks may form is limited by the depth to which wave action may extend with sufficient energy to move the bottom sands; hence it depends on the size of the waves, and therefore in part indirectly on the size of the water body; in the Rhone, the limiting depth is a few decimeters; in Lake Geneva, some ten meters; and in the ocean, from 20 to 188 meters, according to Lyell and Siau. Forel revised De Candolle's law regarding the relation of ripple spacing to the amplitude of the friction-producing movement to read: "The breadth of the ripples, or the distance from one crest to another, is the length of the path followed during a single oscillation by a grain of sand freely transported by the water." The length of this path varies directly as the horizontal amplitude of the oscillatory movement of the water, directly as the velocity of that movement, inversely as the density of the sand, and inversely as the size of the sand grains.

Darwin's paper "On the Formation of Ripple-Mark in Sand" is especially noteworthy for its careful analysis of the vortices which are so important a factor in the construction of the ripples.[1] When symmetrical oscillation ripples were subjected to the action of a steady current, Darwin noticed that not only did sand grains migrate up the weather slope of each ripple with the current, but that they also ascended the lee slopes, apparently *against* the current. This proved conclusively the existence of vortices. Darwin

[1] G. H. Darwin, "On the Formation of Ripple-Mark in Sand," *Proc. Roy. Soc. London*, XXXVI (1883), 18–43.

then proceeded to study the vortices by watching the movements of a drop of ink released from the end of a fine glass tube at that point in the water where the action was to be observed. In this manner the vortices associated with the alternating currents which produce oscillation ripples were analyzed with a high degree of precision, and much light was thrown upon the method of ripple growth. Darwin concluded that "the formation of irregular ripple marks or dunes [current ripples] by a current is due to the vortex which exists on the lee side of any superficial inequality of the bottom; the direct current carries the sand up the weather slope and the vortex up the lee slope. Thus any existing inequalities are increased, and the surface of sand becomes mottled over with irregular dunes." The intermittent friction which De Candolle adduced is not essential in this explanation of current ripples. Oscillation ripples of regular pattern are changed by a continuous current into regularly spaced current ripples; but a uniform current cannot of itself initiate regularly spaced ripple marks. "Regular ripple mark [oscillation ripples] is formed by water which oscillates relatively to the bottom. A pair of vortices, or in some cases four vortices, are established in the water; each set of vortices corresponds to a single ripple crest." Forel's conception of an oscillation ripple as a composite of two current ripples formed alternately by oscillating currents is regarded as correct; but his law for the relation of ripple spacing to amplitude of oscillation is believed to require some modification.

Further studies of ripple-forming vortices were made by Mrs. Hertha Ayrton, the results of which were not published until 1910.[1] With the aid of well-soaked grains of ground black pepper, or of particles of potassium permanganate dissolving and coloring the water while the latter was in oscillation, she observed the formation of vortices and endeavored to explain the mechanics of their growth. Although she expressed disagreement with the conclusions of Darwin and others on certain points, most of her results afford essential confirmation of their main contentions. Some doubt must attach to certain of her deductions, such as

[1] H. Ayrton, "The Origin and Growth of Ripple-mark," *Proc. Roy. Soc. London*, Ser. A., LXXXIV (1910), 285–310.

one to the effect that no ripple-forming vortex occurs in the lee of an obstacle over which a steady current is passing, and that hence "a steady current is unable either to generate or to maintain ripple mark."

The British Association Reports for the years 1889, 1890, and 1891 contain three papers by Reynolds on the action of waves and currents in model estuaries, in which are some valuable observations regarding what may well be termed giant tidal ripples.[1] While experimenting with artificial tidal currents, Reynolds discovered that current ripples were formed in the model estuaries. By making due allowance for the difference in size between the model estuaries and those in nature, he concluded that real tidal currents ought to produce very large current ripples, possibly 7 or 8 feet in height and 80 to 100 feet apart.[2] Some years later Vaughan Cornish discovered natural tidal ripples of the same type as those produced artificially by Reynolds, having a height of 2 feet and an average distance of more than 37 feet from crest to crest.[3] In two later papers Cornish described giant tidal ripples more fully, and illustrated tneir essential features with a large series of beautiful photographs.[4] Some of these ripples have a height of nearly 3 feet above the intervening troughs, and a distance between crests of from 66 to 88 feet in extreme cases. The giant ripples are often covered with ordinary ripple mark, and while Cornish recognized that the larger forms were produced by the continuous steady flow of tidal currents, he was at first inclined to invoke pulsatory currents in order to explain the smaller ripple mark.[5]

[1] Osborne Reynolds, "Report of the Committee Appointed to Investigate the Action of Waves and Currents on the Beds and Foreshores of Estuaries by Means of Working Models," *Rept. British Assoc.* (1889), pp. 327–43; *ibid.* (1890), pp. 512–34; *ibid.* (1891), pp. 386–404.

[2] *Ibid.* (1889), p. 343.

[3] Vaughan Cornish, "On Tidal Sand Ripples above Low-Water Mark," *Rept. British Assoc.* (1900), pp. 733–34.

[4] Vaughan Cornish, "Sand Waves in Tidal Currents," *Geogr. Jour.*, XVIII (1901), 170–202; "On the Formation of Wave Surfaces in Sand," *Scottish Geogr. Mag.*, XVII (1901), 1–11.

[5] Vaughan Cornish, "On Tidal Sand-Ripples above Low-water Mark," *Rept. British Assoc.* (1900), p. 733; "Sand Waves in Tidal Currents," *Geogr. Jour.*, XVIII (1901), 197–98; "On the Formation of Wave Surfaces in Sand," *Scottish Geogr. Mag.*, XVII (1901), 8.

This theory seems to be a survival of De Candolle's erroneous idea that "intermittent friction" is essential to the production of current ripples, and is practically abandoned by Cornish in his more recently published book on *Waves of Sand and Snow*.[1] Gilmore described tidal ripples on the Goodwin Sands having a height of "two or three feet."[2]

It should be noted that all of the giant ripples referred to above belong to the asymmetrical type; they are true current ripples. So far as I am aware no giant oscillation ripples have ever been observed along modern shores. It may be doubted whether tidal currents could form symmetrical ripples, notwithstanding Reynold's suggestion to the contrary.[3] The flow and ebb of the tide constitute an oscillating current, it is true; but the currents are often of unequal force. Where equally strong, each current persists long enough to remodel the ridges formed by the preceding current, giving them an asymmetrical form appropriate to the current operating last. On the other hand, Gilbert has described structures in the Medina sandstone formation of New York which he believed to be giant ripples of the symmetrical type, formed by oscillating currents due to wave action.[4] In dimensions these ridges were similar to the average examples of tidal ripples described by Cornish, having a height of from 6 inches to 3 feet, and a distance from crest to crest of from 10 to 30 feet; but their nearly symmetrical form did not suggest a similar origin. Gilbert reached the tentative conclusion that they were formed by waves 60 feet high in deep water of a broad ocean. This conclusion was criticized by Fairchild, who advanced convincing arguments in support of the opinion that the forms in question were beach structures, possibly successive beach ridges built on the strand.[5] Branner

[1] Vaughan Cornish, *Waves of Sand and Snow* (London, 1914), pp. 289–90.

[2] John Gilmore, *Storm Warriors, or Lifeboat Work on the Goodwin Sands* (London, 1874), pp. 108–9.

[3] Osborne Reynolds, "Report of the Committee Appointed to Investigate the Action of Waves and Currents on the Beds and Foreshores of Estuaries by Means of Working Models," *Rept. British Assoc.* (1889), p. 343.

[4] G. K. Gilbert, "Ripple-Marks and Cross-Bedding," *Bull. Geol. Soc. Amer.*, X (1899), 135–40.

[5] H. L. Fairchild, "Beach Structure in the Medina Sandstone," *Amer. Geologist*, XXVIII (1901), 9–14.

suggested that they might represent fossil beach cusps seen in cross-section.[1]

In 1911 A. P. Brown published a paper entitled "The Formation of Ripple-Marks, Tracks, and Trails," in which he endeavored to show that asymmetrical ripples (current ripples) are formed by deposition, whereas symmetrical ripples (oscillation ripples) result from the erosion of a formerly smooth botton, consequent upon the rippling of overlying water by wind action.[2] His conclusions do not appear to be supported by a sufficient body of convincing evidence, and are opposed by theoretical considerations and by the great body of experimental data already referred to. In presenting his theory this author makes no reference to the many previous investigations of ripple marks of all kinds, the important results of which have been summarized above.

Ripple marks have repeatedly been discussed in connection with the interpretation of fossil ripples found in sedimentary rocks. We need mention but a few of these discussions in the present connection. As early as 1831 Scrope described fossil ripple marks found on slabs of marble, and explained them as due to the oscillatory movements of shallow water.[3] Darwin, starting from the very questionable assumption that a great ebb and flow of the tide is essential to the formation of numerous ripples, concluded that the presence of a large number of ripple marks in a geological formation indicates with a considerable degree of probability that the tides of early times rose higher than those of today.[4] Van Hise figured and described one type of oscillation ripples, and emphasized their value as criteria for determining the original altitude of steeply inclined strata.[5]

[1] J. C. Branner, editorial note, *Jour. Geol.*, IX (1901), 535–36.

[2] A. P. Brown, "The Formation of Ripple-Marks, Tracks, and Trails," *Proc. Assoc. Nat. Sci. Philadelphia*, LXIII (1911), 536–47.

[3] G. P. Scrope, "On the Rippled Markings of Many of the Forest Marble Beds North of Bath, and the Foot-Tracks of Certain Animals Occurring in Great Abundance on Their Surfaces," *Proc. Geol. Soc. London*, I (1831), 317–18.

[4] G. H. Darwin, "On the Geological Importance of the Tides," *Nature*, XXV (1882), 214.

[5] C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *Sixteenth Ann. Rept. U.S. G. S.*, Part I (1896), 719–21.

Spurr showed that where continuous deposition takes place from a current which constantly maintains asymmetrical ripples on the surface over which it flows, the forward movement of the ripples combines with the deposition of heavier and larger fragments in the troughs and lighter particles on the crests to give a peculiar type of false bedding in the resulting formation.[1] Jaggar criticized Spurr's conclusions on the ground that his own experiments and observations indicated that ripple marks could not be produced in heterogeneous material;[2] but Spurr met the criticism with a fuller discussion of the matter in which his original contention is well sustained.[3] A short time previously Sorby had described a somewhat similar phenomenon in a paper[4] printed almost exactly half a century after the publication of his first account of ripple marks, already cited. From an examination of the "ripple-drift" type of false bedding in rocks, Sorby believed that one could "ascertain with approximate accuracy, not only the direction of the current and its velocity in feet per second, but also the rate of deposition in fractions of an inch per minute."[5] Additional discussions of fossil ripple marks are cited by Kindle in his paper referred to at the beginning of this article, but need not be repeated here.

[1] J. E. Spurr, "False Bedding in Stratified Drift Deposits," *Amer. Geologist*, XIII (1894), 43–47.

[2] T. A. Jaggar, Jr., "Some Conditions of Ripple-Mark," *Amer. Geologist*, XIII (1894), 199–201.

[3] J. E. Spurr, "Oscillation and Single-Current Ripple Marks," *Amer. Geologist*, XIII (1894), 201–6.

[4] H. C. Sorby, "On the Application of Quantitative Methods to the Study of the Structure and History of Rocks," *Quart. Jour. Geol. Soc. London*, LXIV (1908), 180–85.

[5] *Ibid.*, pp. 181, 197–99.